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The Impacts of Numerical Schemes on Asymmetric Hurricane Intensification

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Advances in Numerical Methods for Geophysical Modeling

Abstract

The fundamental pathways for tropical cyclone (TC) intensification are explored by considering axisymmetric and asymmetric impulsive thermal perturbations to balanced, TC-like vortices using the dynamic cores of three different nonlinear numerical models. Attempts at reproducing the results of previous work, which used the community model WRF (Nolan and Grasso 2003; NG03), revealed a discrepancy with the impacts of purely asymmetric thermal forcing. The current study finds that thermal asymmetries can have an important, largely positive role on the vortex intensification whereas NG03 and other studies find that asymmetric impacts are negligible.

Analysis of the spectral energetics of each numerical model indicates that the vortex response to asymmetric thermal perturbations is significantly damped in WRF relative to the other models. Spectral kinetic energy budgets show that this anomalous damping is primarily due to the increased removal of kinetic energy from the vertical divergence of the vertical pressure flux, which is related to the flux of inertia-gravity wave energy. The increased kinetic energy in the other two models is shown to originate around the scales of the heating and propagate upscale with time from nonlinear effects. For very large thermal amplitudes (50 K), the anomalous removal of kinetic energy due to inertia-gravity wave activity is much smaller resulting in good agreement between models.

The results of this paper indicate that the numerical treatment of small-scale processes that project strongly onto inertia-gravity wave energy can lead to significant differences in asymmetric TC intensification. Sensitivity tests with different time integration schemes suggest that diffusion entering into the implicit solution procedure is partly responsible for the anomalous damping of energy.

Numerical Models Analyzed: WRF, HIGRAD and NUMA

WRF

Equation Set

- Compressible, nonhydrostatic Euler equations with mass vertical coordinate

$$\frac{\partial \mu u}{\partial t} + \vec{\nabla}\cdot \mu \boldsymbol{u} u = -\frac{\mu}{\rho}\frac{\partial p'}{\partial x} + f\mu v + \mu\kappa\vec{\nabla}^2 u,$$
$$\frac{\partial \mu v}{\partial t} + \vec{\nabla}\cdot \mu \boldsymbol{u} v = -\frac{\mu}{\rho}\frac{\partial p'}{\partial y} - f\mu u + \mu\kappa\vec{\nabla}^2 v,$$
$$\frac{\partial \mu w}{\partial t} + \vec{\nabla}\cdot \mu \boldsymbol{u} w = g\left(\frac{\partial p'}{\partial z} - \mu'\right) + \mu\kappa\vec{\nabla}^2 w,$$
$$\frac{\partial \mu \theta}{\partial t} + \vec{\nabla}\cdot \mu \boldsymbol{u} \theta = \mu\kappa\vec{\nabla}^2 \theta,$$
$$\frac{\partial \mu'}{\partial t} + \vec{\nabla}\cdot \mu \boldsymbol{u} = 0,$$

Spatial Discretization

- Finite-differences, staggered in horizontal and vertical (C-grid)
- $5^{th}/3^{rd}$ order upwind biased for horizontal/vertical advection, also examined $6^{th}/4^{th}$ operators

Time Discretization

- split-explicit (acoustic/gravity wave terms handled on small time step and advection on large time step)
- Small time step horizontally explicit, vertically implicit
- 3^{rd} order Runge-Kutta type scheme for time differencing

Explicit Dissipation

- Disabled 6^{th} order numerical filter, vertical velocity damping, divergence damping, etc.
- Rayleigh absorbing layer at model top (sine squared function)
- Artificial viscosity (Laplacian operator with constant coefficient of 150 m^2/s in x/y/z
- No surface dissipation (free-slip at lower boundary)

HIGRAD and NUMA

Equation Set

- compressible, nonhydrostatic Euler equations with height vertical coordinate

$$\frac{\partial \rho u}{\partial t} + \vec{\nabla}\cdot \rho \boldsymbol{u} u = -\frac{\partial p'}{\partial x} + f\rho v + \rho\kappa\vec{\nabla}^2 u$$
$$\frac{\partial \rho v}{\partial t} + \vec{\nabla}\cdot \rho \boldsymbol{u} v = -\frac{\partial p'}{\partial y} - f\rho u + \rho\kappa\vec{\nabla}^2 v$$
$$\frac{\partial \rho w}{\partial t} + \vec{\nabla}\cdot \rho \boldsymbol{u} w = -\frac{\partial p'}{\partial z} - \rho' g + \rho\kappa\vec{\nabla}^2 w$$
$$\frac{\partial \rho \theta}{\partial t} + \vec{\nabla}\cdot \rho \boldsymbol{u} \theta = \rho\kappa\vec{\nabla}^2 \theta$$
$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot \rho \boldsymbol{u} = 0$$

Spatial Discretization:

- Finite-differences, all variables collocated (A-grid) for HIGRAD
- 2^{nd} order QUICK for horizontal/vertical advection for HIGRAD
- Spectral elements in horizontal and vertical, all variables collocated for NUMA

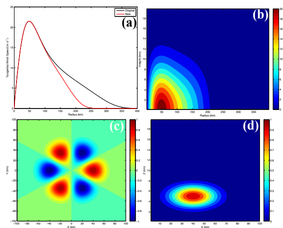
Time Discretization:

- 3D semi-implicit using 1^{st} order forward Euler differencing for HIGRAD
- 3^{rd} and 4^{th} order fully explicit Runge-Kutta available for HIGRAD and NUMA
- 3D semi-implicit using 2^{nd} order leap-frog (LF2) or additive Runge-Kutta (ARK2B) for NUMA
- Several other differencing options available for NUMA

Explicit Dissipation

- Included 6^{th} order numerical filter (HIGRAD only).
- Rayleigh absorbing layer at model top (sine squared function).
- Artificial viscosity (Laplacian operator with constant coefficient of 150 m^2/s in x/y/z
- No surface dissipation (free-slip at lower boundary)
- Robert-Asselin time filter on LF2 time integrator, coefficient=0.2, forward weighted (NUMA)

Setup and Initial Conditions

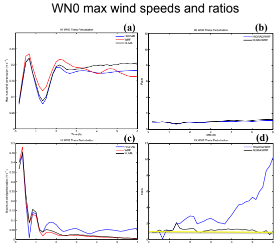


- Axisymmetric initial vortex in gradient and hydrostatic balance
- Structure of baroclinic vortex modeled after real tropical cyclones
- Two types of impulsive thermal (θ) perturbations with amplitudes 1 – 50 K: axisymmetric (WN0) and wavenumber three (WN3)

- HIGRAD and WRF grid spacing of 2 km in horizontal, 333 m in vertical (60 levels)
- NUMA uses 5^{th} order polynomials, 80 elements in x/y and 12 in z (~ 2 km, ~333 m resolution)
- Model domain is 800 km in x/y, 20 km in height (absorber from 16 km to 20 km)
- Dry atmosphere on an f-plane with doubly periodic horizontal boundaries

Small Amplitude (1 K) Perturbation Results

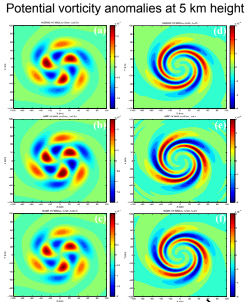
WN0 max wind speeds and ratios



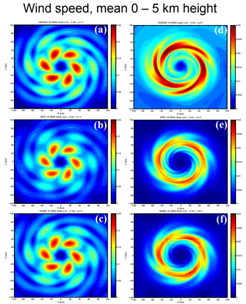
WN3 max wind speed and ratios

Wavenumber Three Response

Potential vorticity anomalies at 5 km height



Wind speed, mean 0 – 5 km height



Angular Momentum Budgets

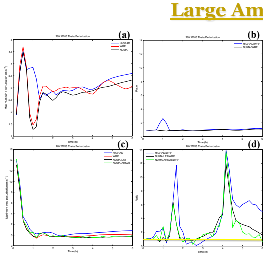
$$\overline{M_a} = r\bar{v} + \frac{f_o r^2}{2}$$

$$\frac{\partial \overline{M_a}}{\partial t} = -\frac{1}{\bar{\rho} r}\frac{\partial\left(r\bar{\rho}\bar{u}\overline{M_a}\right)}{\partial r} - \frac{1}{\bar{\rho}}\frac{\partial\left(\bar{\rho}\bar{w}\overline{M_a}\right)}{\partial z} - \frac{1}{\bar{\rho} r}\frac{\partial\left(r\bar{\rho}\overline{u'M_a'}\right)}{\partial r} - \frac{1}{\bar{\rho}}\frac{\partial\left(\bar{\rho}\overline{w'M_a'}\right)}{\partial z} + r\overline{D_\lambda}$$

STOR. MEAN FLUXES EDDY FLUXES DIFF.

Eddy fluxes very similar across models

Large Amplitude (20 K) Perturbation Results



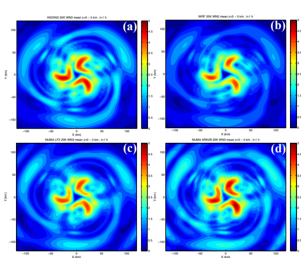
WN0 max winds and ratios

WN3 max winds and ratios

Table 1. Absolute value of the impact ratio, $\left|\frac{WN0}{WN3}\right|$, for impulsive thermal perturbations in each numerical model for various amplitudes. The ratio is listed as a 2 h average over the 4 – 6 h period rounded to the nearest whole number. This is reported in terms of either perturbation maximum wind speed or perturbation integrated kinetic energy. The format is: wind ratio / kinetic energy ratio. The NUMA results use the LF2 time integrator, but similar results were obtained with the ARK2B scheme during this time period.

Amplitude	HIGRAD	WRF	NUMA
1 K	4^{I} / 7^{I}	20^{I} / 1562^{I}	24^{I} / 583^{I}
10 K	3^{I}/ 13^{I}	1596^{I} / 40^{I}	17^{W} / 36^{I}
20 K	5^{I} / 13^{I}	36^{I} / 39^{I}	9^{W} / 16^{I}
30 K	28^{I} / 13^{I}	63^{I} / 24^{I}	13^{W} / 25^{I}
40 K	3^{W} / 217^{W}	13^{I} / 495^{W}	N/A
50 K	3^{W}/ 10^{W}	3^{W} / 6^{W}	N/A

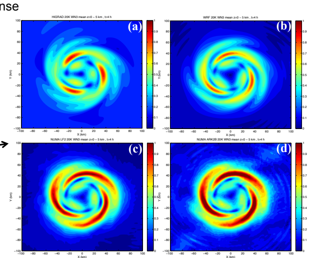
Wavenumber Three Response



Horizontal wind speed (mean 0 – 5 km height)

1 hour

4 hours

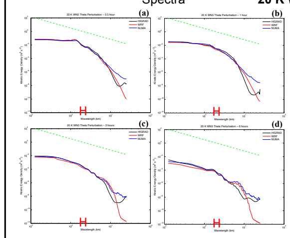


Spectral Dynamics

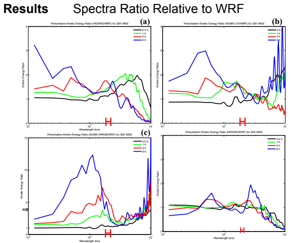
Horizontal Spectral Kinetic Energy $E(k) = 0.5(\hat{u}^2 + \hat{v}^2)$ where hat is Discrete Fourier Transform

Spectra

20 K WN3 Results



Spectra Ratio Relative to WRF



50 K WN3 Results for HIGRAD

Why is WRF More Dissipative than HIGRAD and NUMA ?

Kinetic Energy Budgets in the Spectral Domain

$$\frac{\partial}{\partial t}E(k) = A(k) + P(k) + D(k)$$

$A(k) = -\frac{1}{2}\left(\hat{\boldsymbol{v}}^* \cdot \widehat{\boldsymbol{ADV}} + \hat{\boldsymbol{v}} \cdot \widehat{\boldsymbol{ADV}}^*\right)$, Transport across wavenumbers (nonlinear)

$P(k) = -\frac{1}{2}\left(\hat{\boldsymbol{v}}^* \cdot \widehat{\boldsymbol{PGF}} + \hat{\boldsymbol{v}} \cdot \widehat{\boldsymbol{PGF}}^*\right)$, Pressure effects (see below)

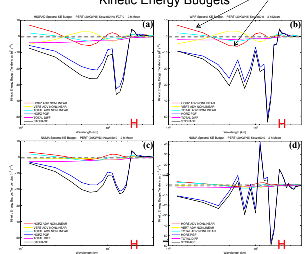
$D(k) = -\frac{1}{2}\left(\hat{\boldsymbol{v}}^* \cdot \widehat{\boldsymbol{DIFF}} + \hat{\boldsymbol{v}} \cdot \widehat{\boldsymbol{DIFF}}^*\right)$. Explicit Diffusion

Applying anelastic mass continuity and hydrostatic equation to pressure term…

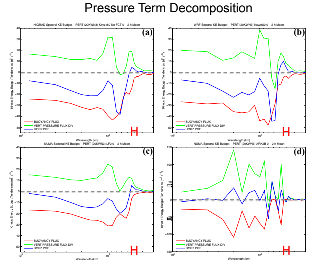
$$P(k) = -\frac{1}{2}\left(\hat{\boldsymbol{v}}^* \cdot \widehat{\boldsymbol{PGF}} + \hat{\boldsymbol{v}} \cdot \widehat{\boldsymbol{PGF}}^*\right) \cong -\frac{1}{2\bar{\rho}}\left(\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\hat{w}^*\hat{p}) + g\hat{w}^*\hat{\rho} + \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\hat{w}\hat{p}^*) + g\hat{w}\hat{\rho}^*\right)$$

Up-scaling of energy

Kinetic Energy Budgets



Pressure Term Decomposition



Conclusions

- Impulsive thermal asymmetries have significant effects in HIGRAD/NUMA, muted in WRF.
  - HIGRAD up to 7 – 10 times larger response in terms of maximum winds.
- Anomalous damping of kinetic energy (KE) in WRF partially due to inertia-gravity waves.
  - Vertical divergence of vertical pressure flux term removes more KE.
- Pressure term dominates KE budget, more room for nonlinear transport in HIGRAD/NUMA.
- Sensitivity to time integration scheme in NUMA suggests temporal diffusion possible culprit.
- Don't know which solutions are correct in absolute sense.
  - However, indicates significant uncertainty in asymmetric TC dynamics.

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